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Correlation of the cyclic cracked round bar test and hydrostatic pressure test for unplasticized polyvinylchloride

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ABSTRACT

The applicability of the cracked round bar (CRB) test according ISO 18489 for the characterization of slow crack growth (SCG) in unplasticized polyvinylchloride (PVC–U) was analyzed by testing three PVC-U pipe compounds with different molecular mass, represented by different intrinsic viscosity numbers (K-values). The tests were conducted at lower stress loading ranges than recommended by the standard. The SCG resistance showed a clear dependency on the K-value resulting in a higher crack resistance with increasing K-value. Moreover, the results of the CRB tests were correlated to hydrostatic pressure tests of PVC-U pipe grades with different K-values. A clear linear correlation between the results of both methods was established, thereby demonstrating a significant acceleration of testing times with the CRB test. With a special focus on EN 1401–1, it was elaborated that the requested minimum failure resistance of 1′000 h in the hydrostatic pressure test at $T = 60$ °C correlates to 97′000 cycles, or 2.7 h, respectively, in the CRB test at $T = 23$ °C.

1. Introduction

For many decades, thermoplastic materials have been used successfully in pipe and underground systems. For water supply and gas distribution, as well as for drainage and sewerage management, the most important polymeric materials are polyethylene (PE), polypropylene (PP), and unplasticized polyvinylchloride (PVC–U) [1]. In case of PVC-U, the first pipes were manufactured in the Bitterfeld-Wolfen chemical industry area in 1934 to be used in different applications, such as the transport of potable water, brewery liquids, or chemicals [2]. Many PVC-U pipe systems of these times are still in operation and have already reached and clearly exceeded their initial design lifetime of 50 years. Different studies on PVC-U pipes after several decades of operation have confirmed further resistance against relevant long-term failure mechanisms, indicating that the expected service life is in excess of 100 years [2–6].

The suitability of a thermoplastic material for high performance pressure rated applications can be advised by hydrostatic pressure tests according to ISO 1167 [7] and ISO 9080 [8]. These standards provide a test and extrapolation method to determine the long-term hydrostatic strength (*LTHS*), which indicates the stress that a pipe will resist without failure for at least 50 years. Extensive research has been conducted with this kind of test, especially for PE [9–18]. Based on a comprehensive understanding of the failure mechanisms of internal pressurized pipes, the hydrostatic pressure test has been implemented into many standards for material and product testing. However, material testing with this method is time consuming as typical failure times are in the range of several thousand hours. For pipes and fittings in non-pressure underground drainage and sewage applications, EN 1401-1 specifies the requirements for PVC-U compounds [19]. As for hydrostatic pressure tests, a resistance of minimum 1′000 h at a temperature of $T = 60$ °C and a hoop stress of $\sigma_{hoop} = 10$ MPa without failure is required.

In order to provide an accelerated test method to characterize the relevant long-term failure resistance of thermoplastic pipe materials against slow crack growth (SCG), the Cracked Round Bar (CRB) test was developed and standardized in ISO 18489 several years ago [20–23]. While the majority of the research with the CRB test was conducted regarding material ranking and lifetime prediction of PE pressure pipe grades [24–29], recent studies have also focused on the applicability of

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Nomenclature

a	crack length in CRB specimen
a_{ini}	initial crack length in CRB specimen
b	ligament radius in CRB specimen
CRB	cracked round bar
D	diameter of CRB specimen
DK_I	stress intensity factor range
$\Delta\sigma_0$	stress loading range in CRB test
f	loading frequency in cyclic CRB test
F_{max}	maximum applied force in CRB test
F_{min}	minimum applied force in CRB test
K, K-value	intrinsic viscosity number for PVC
K_I	stress intensity factor in tensile loading mode I
$K_{I,max}$	maximum stress intensity factor in tensile loading mode I
$K_{I,min}$	minimum stress intensity factor in tensile loading mode I
L	length of CRB specimen
LEFM	linear elastic fracture mechanics
LTHS	long term hydrostatic strength
N_f	number of cycles to failure
PE	polyethylene
PVC-U	unplasticized polyvinylchloride
R	loading ratio in cyclic test
r	radius in CRB specimen
SCG	slow crack growth
σ_{hoop}	hoop stress
σ_{max}	maximum applied stress in CRB test
σ_{min}	minimum applied stress in CRB test
t_f	time to failure
Y	geometry factor

the CRB test to other thermoplastic materials such as PP, PVC-U, or PA12 [30–33]. Moreover, it has already been demonstrated that this accelerated SCG ranking test is also suitable for the characterization of recycled PE, PP and PVC-U [34,35].

The current paper is dedicated to provide new systematically data in order to evaluate the applicability of the CRB test for an accelerated SCG characterization of PVC-U compounds which have been designed for sewage and stormwater pipe systems. A special focus is given to the sensitivity of this test with regard to the K-value, which is as an indication of the molecular mass of the polymer. Consequently, the main objective of this study is to establish a correlation between the results of the CRB test and the hydrostatic pressure test, as well as with the requirements as specified in EN 1401–1.

2. Background

The failure mechanisms of internally pressurized thermoplastic pipes have been investigated extensively and are well understood [9–15]. Depending on the internal pressure and the created hoop stress σ_{hoop}, respectively, three different failure stages may occur which are shown schematically in Fig. 1. At relatively high σ_{hoop}, ductile failure, stage I, will take place after relatively short loading times. With decreasing σ_{hoop}, the pipe failure changes into a quasi-brittle mode which is characterized by crack initiation and SCG, also referred to as stage II failure. Many thermoplastic materials exhibit a transition knee along the failure curve when changing from stage I failure to stage II failure. With further decreasing σ_{hoop} and even longer loading time, the resistance against thermo-oxidative degradation becomes relevant and the pipe fails by material aging, stage III, almost independent of the applied internal pressure.

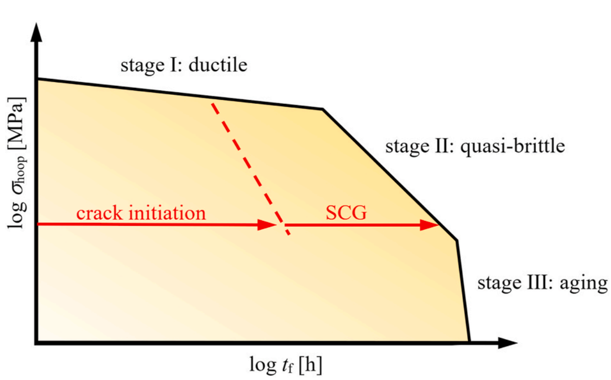

Fig. 1. Characteristic failure behavior of internally pressurized thermoplastic pipes.

While stage I failure can be prevented by the consideration of mechanical short-term properties, and stage III failure is basically controlled by stabilizer systems, stage II failure, governed by SCG, has been accepted as the most critical failure for long-term pipe applications. Similar to polyolefins, the typical failure modes of stage I and stage II have also been observed for PVC-U [17,36–38]. For PVC-U, the SCG resistance (stage II) is directly linked to the K-value of the material, which is a representative value of the viscosity and the average molecular mass, respectively [17,39,40]. For pipe applications, typical values lie within a range from K57 to K68 [41].

Slow crack growth is a stress driven mechanism which can be described by concepts of linear elastic fracture mechanics (LEFM) [42–49]. Initially developed to describe crack propagation in metals, a large body of scientific work also demonstrated the applicability of LEFM to thermoplastic materials [11,36,50–60]. The crack driving force is controlled by stress and can be described by the stress intensity factor K_I according to equation (1), which is a function of the nominal loading σ, the crack length a and a geometrical factor Y that is well known for many specimens and component shapes [61].

$$K_I = \sigma \cdot \sqrt{a} \cdot Y \tag{1}$$

The index "I" in K_I specifies the loading mode, which in case of mode I refers to pure crack opening conditions. For many practical applications, mode I represents the critical and dominating loading mode [36]. The available tools of LEFM allow a reliable characterization of the crack growth phenomena under crack opening mode in many engineering structures. However, under specific conditions other modes may be relevant such as in-plane shear, mode II, or out-of-plane shear, mode III [36,42,48,49]. Complex loading may even result in mixed mode conditions such as mode I/II [62–64] or mode I/III [65–67].

Comprehensive studies with polymeric materials have demonstrated that within the applicability of LEFM, the same physical processes are responsible for SCG under static as well as for cyclic loads [14,21,36,37,50,60,68–76]. Specific research on PVC has shown that the SCG kinetics under fatigue loadings can be correlated to static loading, and that within the boundaries of LEFM the same physical mechanisms are responsible for SCG under cyclic as well as under static loading [37,38,43,76].

Hence, cyclic loading is a reliable way to accelerate the mechanisms of crack initiation and propagation in laboratory tests. In cyclic tests, the loading conditions R are defined by the ratio of minimal to maximal loading, expresses by the minimum and maximum applied force F_{min} and F_{max}, the minimum and maximum stress σ_{min} and σ_{max}, or minimum and maximum stress intensity factor $K_{I,min}$ and $K_{I,min}$, respectively (equation (2)), and the range of minimal to maximal K_I becomes the crack driving force ΔK_I (equation (3)). The K_I in a CRB specimen can be calculated according to equations (4)–(6), where F is the applied force, a

is the crack length and r is the specimen radius [21,61,77,78].

$$R = \frac{F_{min}}{F_{max}} = \frac{\sigma_{min}}{\sigma_{max}} = \frac{K_{I,min}}{K_{I,max}} \tag{2}$$

$$\Delta K_I = K_{I,max} - K_{Imin} = K_{I,\ max} \cdot (1 - R) \tag{3}$$

$$K_I = \frac{F}{\pi \cdot b^2} \cdot \sqrt{\frac{\pi \cdot a \cdot b}{r}} \cdot f\left(\frac{b}{r}\right) \tag{4}$$

$$b = r - a \tag{5}$$

$$f\left(\frac{b}{r}\right) = \frac{1}{2} \cdot \left[1 + \frac{1}{2} \cdot \left(\frac{b}{r}\right) + \frac{3}{8} \cdot \left(\frac{b}{r}\right)^2 - 0.363 \cdot \left(\frac{b}{r}\right)^3 + 0.731 \cdot \left(\frac{b}{r}\right)^4\right] \tag{6}$$

3. Experimental

Previous studies have demonstrated that the stage II failure times of PVC-U in hydrostatic pressure tests increase with increasing K-values [17]. To investigate the sensitivity of the CRB test with regard to the K-value, PVC-U pipe compounds with three different K-values of K57, K62, and K66 were manufactured. The formulations were based on a calcium/zinc stearate for heat stabilization and several other additives usually used for PVC-U pipe compounds, including an amount of 12.75% of chalk which is in agreement with EN 1401–1 [19]. The materials were compounded with a twin-screw extruder of the type Gottfert DS-35 using a 5-string die with medium screw compression, a screw speed of 30 rpm, and an output rate of approx. 18 kg/h. The extruded strings were cut into granules with a cutter of the type Dreher (Dreher Maschinenbau GmbH), and further processed with a kneader of the type Brabender Plastograph. The homogenized PVC was directly transferred from the kneader into a customized mold in which it was cooled down in order to produce sheets with the dimensions of ~10.5 × 20 × 120 mm^3. From these sheets, cylindrical bars with a diameter of $D = 10.2$ (±0.1) mm and a length of $L = 100$ mm were mechanically manufactured by cutting and drilling with a conventional saw and lathe, respectively. Finally, these bars were circumferentially notched with a razor-blade to create CRB specimens with an initial crack length of $a_{ini} = 1$ (±0.1) mm.

All CRB tests within this study were executed on an electrodynamical testing system of the type ElectroPuls™ E3000 (Instron, Norwood, MA, USA). The tests were conducted under standard laboratory conditions at ambient temperature of 23 °C (±2 °C) and a relative humidity of 50% (±10%). The force-controlled loading stress range $\Delta\sigma_0$ was applied with a frequency of $f = 10$ Hz, as recommended by ISO 18489 [20]. Thermoplastic materials are generally sensitive to hysteretic heating. For PE, a study with CRB tests has shown that no significant changes in the failure curve characteristics appear up loading frequencies to $f = 20$ Hz [79]. Moreover, it has been demonstrated that PVC-U shows no significant hysteretic heating effects at the crack tip even up to $f = 100$ Hz [43]. For each material, five specimens were tested at different loading stress ranges between $\Delta\sigma_0 = 7$ and 11 MPa. During the test, the number of cycles to failure of the specimen N_f was recorded. For an exact calculation of the effectively applied load, the initial crack length a_{ini} of the CRB specimen was measured after each test with a light microscope of the type BX51 (Olympus; Vienna, Austria) and data evaluation was carried out using the software analySIS 3.2 (Soft Imaging Systems GmbH; Munich, Germany).

Due to limitations in the sheet thickness, CRB specimens with only $D = 10.2$ mm were used in this study, in contrast to the specimen diameter of $D = 14$ mm recommended in the testing standard ISO 18489. Annex A of ISO 18489 provides information on how to compare different CRB diameters to each other - not via $\Delta\sigma_0$ but based on ΔK_I. This allows a mathematical shift of the loading stress range via the stress intensity factor from a small specimen to a normalized standard specimen diameter of $D = 14$ mm. Accordingly, to correlate the CRB test results of the current study with the hydrostatic pressure test results, the values of the failure regression lines at $\Delta K_I = 0{,}44$ $MPam^{0.5}$ were determined, which correspond to $\Delta\sigma_0 = 8.5$ MPa in a standard CRB specimen diameter according to ISO 18489 [20].

To compare the CRB test with hydrostatic pressure test, suitable failure data were required. For the above-mentioned compounds, previously determined data for K57, K60, K62, and K65 was available. This data will be labelled as reference data I in this paper. In general, only limited data from hydrostatic pressure tests with PVC-U pipe compounds is available in technical and scientific literature. A rare summary of hydrostatic pressure tests of PVC-U pipe compounds with K-values from K51 to K71 [17] has been used as further source for the correlation. This data will subsequently be labelled as reference data II.

For the correlation of the reference data I and II with the CRB test, the values of stage II failure curves at a testing temperature of $T = 60$ °C and a hoop stress $\sigma_{hoop} = 10$ MPa were used. This stress level was selected according to EN 1401–1 [19], which specifies the minimum resistance of 1′000 h for PVC-U pipes in hydrostatic pressure tests without failure.

4. Results and discussion

Details of the specimen dimensions D and a_{ini}, testing parameters F_{max} and F_{min}, applied testing loads $\Delta\sigma_0$ and corresponding stress intensity factor range ΔK_I, and number of cycles to failure N_f of the CRB tests conducted within this study are summarized in Table 1. Therein, $\Delta\sigma_0$ is the loading stress range of the CRB specimens as tested which varies between $\Delta\sigma_0 = 6.2$ and 11.2 MPa. In Fig. 2 the number of cycles to failure N_f as a function of the stress intensity factor ranges ΔK_I are shown in a log-log scale, forming a typical linear characteristic of the failure curve regression lines. To correlate the CRB tests with hydrostatic pressure tests, the values of the regression lines at $\Delta K_I = 0.44$ $MPam^{0.5}$ were determined and summarized in Table 2.

A clear difference in the failure curves of the PVC-U compounds can be observed, showing an increasing SCG resistance with increasing K-value. The physical processes during SCG are dominated by the development and breakdown of polymer crazes. Craze development is a stress driven phenomena caused by the formation of fibrils and the ability of macromolecules for molecular disentanglement [11,56,80,81]. In PVC, mechanical and fracture mechanical material properties are mainly defined by the crystalline microdomain structure of the primary particles. The polymer chains inside a primary particle are held together and cannot interact with other primary particles. At high temperatures, e.g. during processing, crystallites at the primary particle surface melt and interact with macromolecules of other primary particles. While inside the primary particles the crystalline structure is not significantly changing, during the cooling process the interface molecules connect the adjacent primary particles together into a three dimensional network by newly formed crystallites [80–84]. This fusion-like thermodynamic behavior is characteristical for PVC and also describes the observations in the CRB tests: Longer macromolecules (higher K-value) not only statistically connect more crystallites within the primary particles, but they also create a higher number and density of tie molecules. Consequently, with higher K-value, a stronger tie molecule network between the primary particles is provided which results in a higher resistance against molecular disentanglement and SCG, respectively.

Fig. 3 shows a scanning electron microscope image of the CRB fracture surface of sample K57-1. In the overview (Fig. 3, left), the typical fracture surface appearance in dynamically loaded CRB specimens can be noticed. The crack was initiated at the circumferential razor-blade notch tip and propagated into the remaining ligament area of the CRB specimen. During the final phase of SCG, an eccentric crack propagation occurs towards the lower left area in the image. This kind of eccentricity of SCG in CRB tests is characteristical and studies on PE have proven that this effect appears only during the final phase of brittle-ductile transition [79]. On a macroscopic scale, the SCG area looks rather smooth, while a clear increase in the surface roughness of the final ductile failure area can be noticed. A 2000-fold magnification

Table 1
Specimen Diameter D, initial crack length a_{ini}, maximum test load F_{max}, minimum test load F_{min}, applied loading stress range $\Delta\sigma_0$, stress intensity factor range ΔK_I, and number of cycles to failure N_f for CRB specimens of PVC-U compounds with different K-values at a temperature of $T = 23$ °C.

Sample	D[mm]	a_{ini}[mm]	F_{max}[N]	F_{min}[N]	$\Delta\sigma_0$[MPa]	ΔK_I[MPam$^{0.5}$]	N_f[cycles]
K57-1	10.23	1.02	510	51	8.70	0.387	100′335
K57-2	10.22	1.04	530	53	9.14	0.,407	80′612
K57-3	10.20	1.04	420	42	7.30	0.325	247′021
K57-4	10.21	1.07	360	36	6.35	0.284	373′802
K57-5	10.23	1.02	471	47	8.04	0.357	130′130
K62-1	10.23	1.06	640	64	11.13	0.497	70′334
K62-2	10.24	1.00	471	47	7.93	0.351	271′971
K62-3	10.17	1.05	530	53	9.34	0.416	144′604
K62-4	10.21	1.10	420	42	7.51	0.337	394′858
K62-5	10.25	1.06	360	36	6.24	0.279	689′455
K66-1	10.18	1.02	580	58	10.06	0.447	284′212
K66-2	10.22	1.11	420	42	7.51	0.338	885′223
K66-3	10.22	0.98	420	42	7.05	0.311	1′277′508
K66-4	10.21	1.01	530	53	9.07	0.402	371′752
K66-5	10.28	1.10	471	47	8.26	0.372	611′085

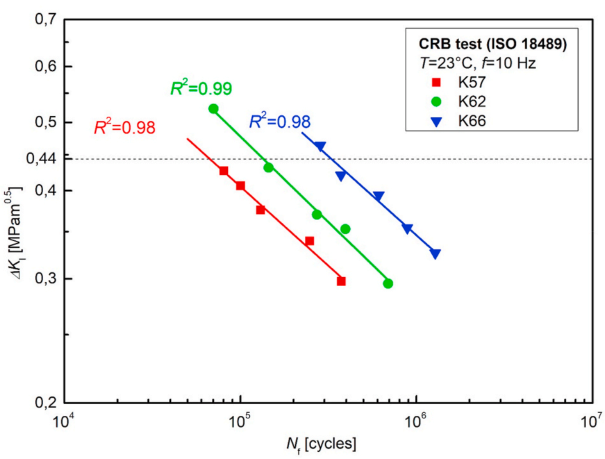

Fig. 2. Number of cycles to failure N_f as a function of the stress intensity factor range ΔK_I in the CRB test at a temperature of $T = 23$ °C and a loading frequency of $f = 10$ Hz for PVC-U pipe compounds with K-values K57, K62, and K66.

Table 2
Number of cycles to failure N_f of the CRB failure curves according to ISO 18489 at $\Delta K_I = 0.44$ MPam$^{0.5}$ and $T = 23$ °C, and failure times of the *LTHS* lines of hydrostatic pressure tests at $\sigma_{hoop} = 10$ MPa and $T = 60$ °C for PVC-U with different K-values.

K-value [-]	N_f CRB at $\Delta K_I = 0.44$ MPam$^{0.5}$/$T = 23$ °C [cycles]	t_f of *LTHS* at $\sigma_{hoop} = 10$ MPa/T = 60 °C[h]		
		reference I	reference II [17]	Average (Fig. 6)
K51	–	–	10	–
K57	66′711	478	–	260
K58	–	–	378	–
K60	–	1′032	–	–
K61	–	–	1′368	–
K62	134′885	2′665	–	4′407
K65	–	22′807	60′600	–
K66	327′922	–	–	42′470

of the quasi-brittle fracture surface area is shown in Fig. 3 on the right. In this microscopic scale, clear fibrillar structures can be observed which remained on the fracture surface as evidence for crazing during SCG. Similar fracture surface appearance for PVC-U after cyclic and static loaded SCG failure have been observed in previous studies [38,76].

In Fig. 4, the results of the hydrostatic pressure tests at $T = 60$ °C for PVC-U with K-values of K57, K60, K62, and K65 are summarized. All data represent stage II failure mode, and no ductile stage I failure data is included in this chart. In log-log scale, a linear correlation between σ_{hoop} and the failure time t_f can be noticed, and according to ISO 9080 [8] a linear regression provides the failure curve for the *LTHS*. The results show that with increasing K-value also the pipe failure times increase correspondingly. To correlate these results with the CRB test, the values of *LTHS* at $\sigma_{hoop} = 10$ MPa were determined and summarized in Table 2 as “reference I”.

For further reference, hydrostatic pressure test data for PVC-U with different K-values between K51 and K71 at $T = 60$ °C have been taken from published work [17] and summarized in Fig. 5. These results clearly indicate a ductile-brittle transition knee for the materials with K58 to K65. While for the material K51 only brittle failure was obtained, the pipe samples with K68 and K71 show only ductile failure at relatively high hoop stresses up to testing times of more than 32′000 h or approx. 3.7 years, respectively. Similar to the findings presented before, a clear dependency of the *LTHS* lines on the K-value can be observed, showing longer pipe failure times with increasing K-value. To correlate these results with the CRB test, the values of *LTHS* at $\sigma_{hoop} = 10$ MPa were determined and summarized in Table 2 as “reference II”.

As not exactly the same K-values were tested in the CRB test and the hydrostatic pressure tests, the following approach was applied to correlate the two methods with each other. For reference data I, values at the same K-values of K57 and K62 are available in both tests which were correlated directly. In case of the CRB data with K66, the comparison with the hydrostatic pressure test was done with K65, accepting a tolerance of ±1 in the K-value. For reference data II, no data for the same K-values are available. In that case, the CRB data of K57, K62, and K66 were correlated to the hydrostatic pressure test data of the samples K58, K61, and K65, again accepting a tolerance of ±1 in the K value. In addition, the relationship of the *LTHS* failure times at $\sigma_{hoop} = 10$ MPa of reference data I and II with the respective K-values was created and illustrated in Fig. 6. In linear-log scale, within the available range of K51 to K65 the data show a linear dependency to each other. The linear regression line results into equation (7) which was used to calculate average *LTHS* failure times at K52, K57, and K66 as additional direct correlation data to the CRB tests. The results are summarized as “average” in Table 2.

$$t_f = 2.479 \cdot 10^{-12} \cdot e^{0.566 \cdot K} \tag{7}$$

The data summarized in Table 2 is graphically shown in Fig. 7. In log-log scale, a clear linear correlation of N_f at $T = 23$ °C in the CRB test at $\Delta K_I = 0.44$ MPa - which corresponds to $\Delta\sigma_0 = 8.5$ MPa in a CRB specimen according to ISO 18489 - with the *LTHS* of the hydrostatic pressure tests at $\sigma_{hoop} = 10$ MPa and $T = 60$ °C is established. While the failure times in the hydrostatic pressure tests at this value vary almost across

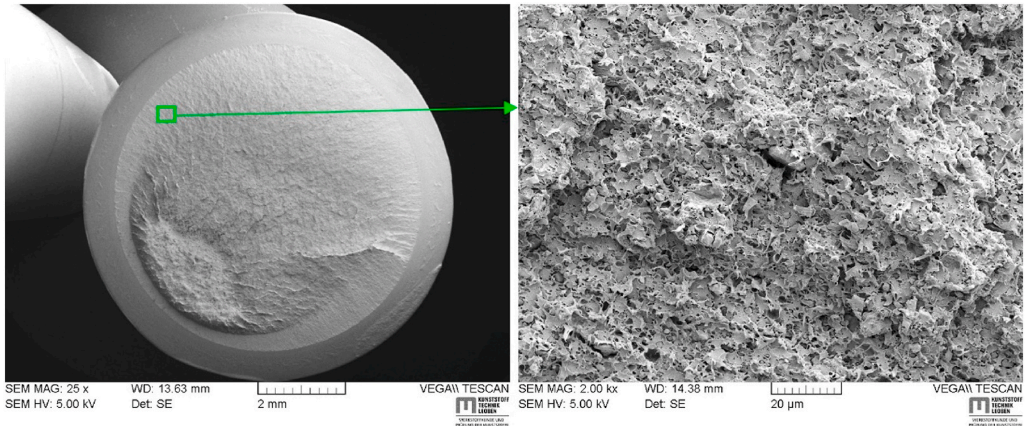

Fig. 3. Scanning electron microscope image of the CRB fracture surface of sample K57-1. Left: overview; right: 2000-fold magnification of SCG area.

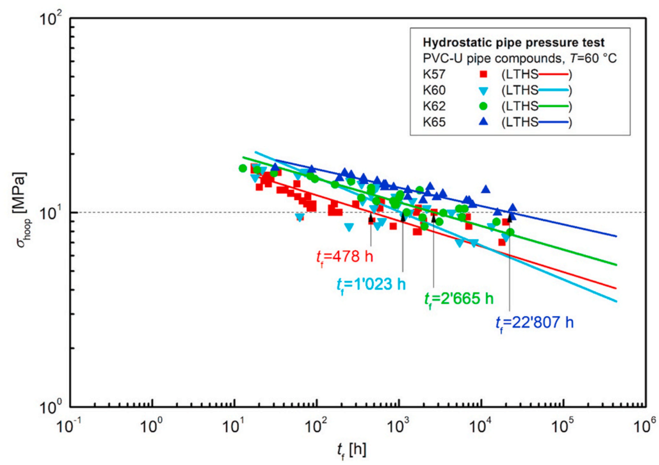

Fig. 4. Failure data points and *LTHS* curves in the hydrostatic pressure test at $T = 60$ °C for PVC-U with different K-values between K57 and K65 (reference data I).

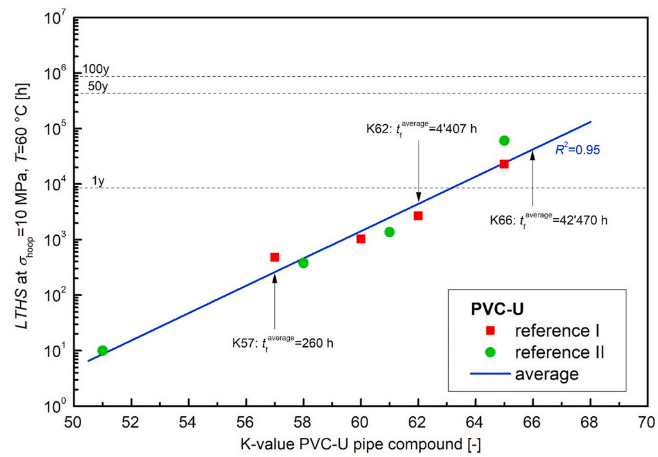

Fig. 6. Correlation of the K-value of different PVC-U pipe compounds and the respective LTHS from hydrostatic pressure tests at $\sigma_{hoop} = 10$ MPa and $T = 60$ °C.

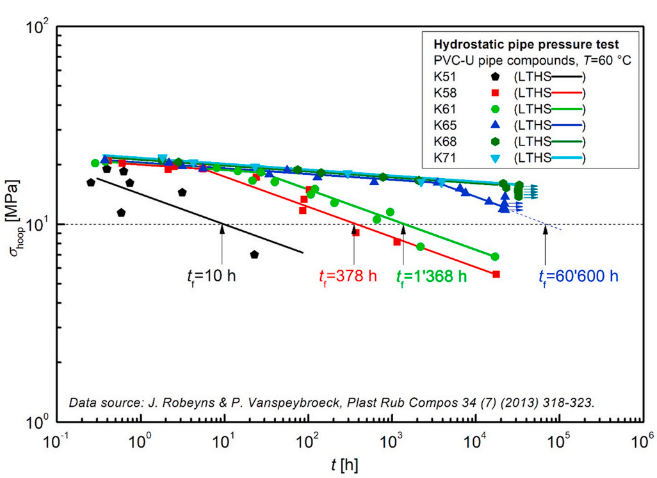

Fig. 5. Failure data points and *LTHS* curves in the hydrostatic pressure test at $T = 60$ °C for PVC-U with K-values between K51 and K71. Data were taken from published work [17].

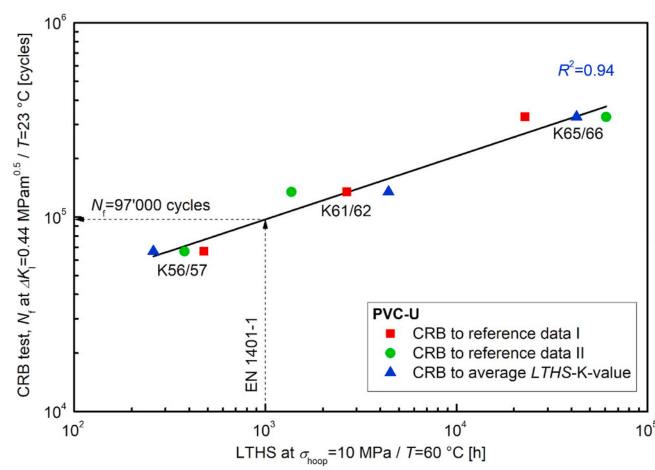

Fig. 7. Correlation of PVC-U in the hydrostatic pressure test at $\sigma_{hoop} = 10$ MPa and $T = 60$ °C with the CRB test at $\Delta K_I = 0.44$ MPa, which equates to $\Delta\sigma_0 = 8.5$ MPa in a CRB specimen according to ISO 18489, and $T = 23$ °C.

three magnitudes from 378 h (~16 days) to 60′600 h (~2′525 days), the numbers of cycle to failure in the CRB tests stay within the range of 66′711 cycles (~2 h) to 327′922 (~9 h), demonstrating a clear benefit for the CRB as it provides a significant reduction in testing times.

For PVC-U pipes and fittings in non-pressure applications, EN 1401–1 is the relevant standard and a minimum failure resistance in hydrostatic pressure tests of 1′000 h at $T = 60$ °C and $\sigma_{hoop} = 10$ MPa is requested [19]. This requirement has been implemented into Fig. 7 and lead to a minimum required number of cycles in the CRB test according to ISO 18489 at $\Delta\sigma_0 = 8.5$ MPa and $T = 23$ °C of $N_f = 97'000$ cycles, which equates to a testing time of 2.7 h. In comparison to the 1′000 h requirement of the hydrostatic pressure test in EN 1401–1, the CRB test accelerates the material characterization by the factor of 370. The possibility to generate representative stage II failure data within only a few hours makes the CRB test attractive for a quick characterization of the SCG during material and compound development, as well as for a regularly applied test method in quality assurance or batch release.

5. Conclusions

The current paper demonstrates the applicability of the CRB test for a fracture mechanical characterization of PVC-U. In contrast to the recommendations in ISO 18489, which are optimized for PE-HD pipe grades, lower loading stress levels were applied to determine the stage II failure regression lines of PVC-U compounds with different K-values. The CRB test provides a high sensitivity to the K-value which is directly linked to a stronger tie molecule network, higher resistance against molecular disentanglements, and consequently to a higher SCG resistance of the material.

The CRB test data at $T = 23$ °C was combined with *LTHS* values from hydrostatic pressure tests at $T = 60$ °C, resulting in a clear linear correlation of both methods. While hydrostatic pressure tests require several hundreds to thousands of hours to generate the relevant failure data, the determination of the stage II failure curves with the CRB test was possible within a few days only. Special attention was given to the interpretation of EN 1401–1, which specifies the requirement for PVC-U pipes and fittings in non-pressure applications. The requested minimum resistance of 1′000 h in the hydrostatic pressure test correlates to a number of cycles to failure of $N_f = 97'000$ cycles, or 2.7 h respectively, in the CRB test. This significant reduction of testing times demonstrates the high potential of the CRB test for being implemented into relevant testing and product standards and to enable the use of this test method for a quick material development as well as for quality control.

CRediT authorship contribution statement

Andreas Frank: Conceptualization, Project administration, Funding acquisition, Methodology, Writing – original draft. **Mario Messiha:** Methodology, Investigation. **Thomas Koch:** Writing – review & editing. **Jan Poduška:** Investigation, Writing – review & editing. **Pavel Hutař:** Resources. **Florian Arbeiter:** Validation, Writing – review & editing. **Gerald Pinter:** Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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